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# OUR PRESENT KNOWLEDGE OF ISOSTASY FROM GEODETIC EVIDENCE

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For a number of years investigations have been made by the Coast and Geodetic Survey upon the subject of isostasy. The first work was done under the direction of Professor John F. Hayford in connection with a study of the deflection of the vertical and the determination of the shape and size of the earth. The later work consisted of investigations of the effect of topography and isostatic compensation upon the intensity of gravity. This work was started by Professor Hayford, and the first report on it was made to the International Geodetic Association.[1] The first comprehensive report on this work was made by Professor Hayford and the writer in Special Publication No. 10 of the Coast and Geodetic Survey which appeared in 1912.[2] The investigations of gravity and isostasy were continued under the direction of the writer, and the results have been published in two reports, one appearing in 1912 and the other in 1917.[3]

As is well known, the theory of isostasy postulates that at some depth below sea-level forces are in equilibrium and, therefore, that each column of unit cross-section extending from the depth of compensation to the surface of the earth contains the same amount of matter; or, to be more exact, it may be stated that each column of unit cross-section which extends from the depth of compensation to the sea-level surface has the same weight.

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[1] *Geodetic Operations in the United States, 1906–9*, a report to the sixteenth general conference of the International Geodetic Association. Separate publication of the Coast and Geodetic Survey (not numbered), 1909.

[2] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Special Publication No. 10, Coast and Geodetic Survey, 1912.

[3] *Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Second Paper, Special Publication No. 12, Coast and Geodetic Survey, 1912; *Investigations of Gravity and Isostasy*, Special Publication No. 40, Coast and Geodetic Survey, 1917.

One of the main objects of the investigations made in the Coast and Geodetic Survey is to determine to what extent isostasy is proved to exist. Other objects are to determine, if possible, the method of distribution of the compensation, horizontally and vertically, with respect to each topographic feature, and to discover, if possible, the cause or causes of the gravity anomaly which cannot be accounted for by the topography and by the isostatic compensation of the topography. By topography is meant the material above sea-level on the continents and islands and the deficiency of density in the matter between the ocean surface and the bottom of the oceans.

Professor Hayford made the following statement in his second publication on the figure of the earth and isostasy. "One may properly characterize the isostatic compensation as departing, on an average, less than one-tenth from completeness or perfection. The average elevation of the United States above sea-level being about 2,500 feet, this average departure of less than one-tenth part from complete compensation corresponds to excesses or deficiencies of mass represented by a stratum only 250 feet thick, on an average."[1]

Professor Hayford based his conclusion upon the fact that the mean residual or deflection of the vertical, after the isostatic correction was applied, was 2.91 seconds of arc. After only the topographic deflection was applied, the residual was 30.37 seconds. It is seen, therefore, that the application of the effect of the isostatic compensation reduced the average residual from 30.37 to 2.91 seconds.

In making the corrections for the effect of the isostatic compensation, Professor Hayford assumed that the compensation was directly under the topographic feature and that it was distributed uniformly to the depth of compensation. This depth of compensation was an unknown quantity, to be determined from the available data. The depth derived by him is 122 km.

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[1] *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, special publication (not numbered) of the Coast and Geodetic Survey.

Professor Hayford stated that the anomalies or deflections of the vertical, resulting after the application of the correction for isostatic compensation as well as for the topography, would be an indication of the extent to which the conditions postulated would not be true.

Professor Hayford should have stated that the compensation departed from perfection only 10 per cent locally, for there is no indication that there is a departure of 10 per cent from the perfect state for the whole country. Some of the anomalies were positive and others negative and these tend to balance for the whole area.

Several tests were made by Professor Hayford to show the result of other methods of vertical distribution of the isostatic compensation than the one of uniformity. If the isostatic compensation is uniformly distributed through a stratum 10 miles thick, he found the most probable depth for the bottom of this stratum to be 40 miles. If the isostatic compensation is distributed with respect to depth, according to the law postulated by Professor T. C. Chamberlin, the most probable value of the limiting depth is 193 miles. The method of distribution of the compensation by Professor Chamberlin's method is given on pages 159 and 160 of *The Figure of the Earth and Isostasy from Measurements in the United States*. This is the first report[1] on the deflection of the vertical and isostasy. In regard to the Chamberlin method, Hayford said: "It is not possible to ascertain whether this compensation is more probable than the solution G compensation, uniformly distributed from the surface to a depth of 70.67 miles, since the two sets of computed deflections agree so closely that their differences are much smaller than the accidental errors."

When the investigations of gravity and isostasy were undertaken, it was concluded that the compensation should be distributed uniformly to a depth of 113.7 km., which was the depth determined by Hayford in his first investigation of the deflection of the vertical and isostasy. The uniform distribution was adopted because it made easier the preparation of the tables with which the computation of the effect of the isostatic compensation was made. It was also believed that this method of distribution was as probable

[1] Special report (not numbered) of the Coast and Geodetic Survey, 1909.

as any other simple method of distributing the isostatic compensation. It was realized by Professor Hayford and by the writer of this paper that uniform distribution to the depth of compensation could not be true at all places; yet it was thought that the departures from normal densities in the lithosphere due to the compensation were heterogeneous and that for a large area the effect would therefore be practically that of uniform deviation from normal.

What follows in this paper is largely based upon the results of the most recent investigation of gravity and isostasy (Special Publication No. 40).

In this investigation there were used 219 stations in the United States, 42 in Canada, 73 in India, and 40 other stations, principally in Europe—374 in all.

There were certain phases of the investigation which had to be confined to stations in the United States, owing to lack of data for the other stations. These consisted of tests to show whether local or regional distribution of compensation horizontally is the more probable, and also of tests to derive the most probable value of the depth of compensation based upon uniform distribution of the compensation vertically from the surface of the ground to the depth of compensation.

Three hundred and fifty-eight stations were used for the determination of the most probable values for the constants in the gravity formula which gives the value of gravity, $\gamma_0$, at sea-level for any latitude, $\phi$. This formula is

$$\gamma_0 = 978.039\ (1 + 0.005294 \sin^2 \phi - 0.000007 \sin^2 2\phi).$$

It is a remarkable fact that this formula agrees almost exactly with the formula derived in 1912 from only 122 stations in the United States alone. That formula was

$$\gamma_0 = 978.038\ (1 + 0.005304 \sin^2 \phi - 0.000007 \sin^2 2\phi).$$

This agreement between the derived formulas is a clear indication that isostasy is present to practically the same degree in other countries as it is in the United States.

The average gravity anomaly with regard to sign for stations in the United States by the adopted method of reducing for isostasy is −0.003 dyne, while the average without regard to sign for these stations is 0.020 dyne. An anomaly is the difference between the observed and computed values of gravity. The computed value has corrections applied for the elevation of station above sea-level and for the effect of the attraction of the topography of the whole world and of the opposite effect of the isostatic compensation of the topography. The topography is considered to be that material on the continents and on islands which is above sea-level and the deficiency of material in the oceans.

An anomaly of 0.020 dyne in terms of mass is here given in order that the reader may have a clear conception of the magnitude of the deviation of the gravity from normal. If we should have a disk of material directly under a gravity station and if the disk should be of normal density, 20 km. in diameter and about 600 feet thick, the attraction on a gram mass at the station would be 0.020 dyne. An anomaly of 0.001 dyne represents the attraction of a disk of material of indefinite horizontal extent and about 30 feet in thickness on a gram mass located near the center of the surface.

The anomalies by the isostatic method varied from +0.059 at Minneapolis, Minnesota, to −0.093 dyne at Seattle, Washington. There were only ten anomalies which were greater than 0.050 dyne.

When a correction was applied to the computed value of gravity for the effect of the topography, but none for the isostatic compensation, the mean anomaly with regard to sign for the stations in the United States was −0.037 dyne. The corresponding mean without regard to sign for the stations in the United States was 0.050 dyne.

The fact that the gravity anomalies were more nearly eliminated by the isostatic method of reduction than by the methods where isostatic compensation was not considered is strong evidence in favor of the former method.

We must conclude, however, that no method can be near the truth unless it has a rather general application to different sections of the country and to different classes of topography. In order to test the methods of reductions by this theory, the stations were arranged in five groups according to the topography. The anomalies with and without regard to sign for the several classes of topography and for the two methods of reduction—one taking into account the topography and compensation, and the other only the topography—are given in Table I. To make it easier to refer to these methods the first will be called the Hayford method and the other the Bouguer method.

TABLE I

MEAN ANOMALIES

| CHARACTER OF STATIONS | NUMBER OF STATIONS | MEAN ANOMALIES | | | |
|---|---|---|---|---|---|
| | | With Regard to Sign | | Without Regard to Sign | |
| | | Hayford; Depth, 113.7 km. | Bouguer | Hayford; Depth, 113.7 km. | Bouguer |
| Coast stations | 27 | −0.009 | +0.017 | 0.018 | 0.021 |
| Stations near coast | 46 | − .001 | + .004 | .021 | .025 |
| Stations in interior, not in mountainous regions | 88 | − .001 | − .028 | .019 | .033 |
| Stations in mountainous regions, below general level | 36 | − .003 | − .107 | .020 | .108 |
| Stations in mountainous regions, above general level | 20 | + .001 | − .110 | .017 | .111 |
| All stations (except the two Seattle stations) | 217 | − .002 | − .036 | .019 | .049 |
| All stations | 219 | −0.003 | −0.037 | 0.020 | 0.050 |

This table shows that the Hayford reduction gives about the same values without regard to sign for each class of topography while the mean anomalies with regard to sign have a very small range if we do not consider the 27 stations at the coasts. It is probable that the coast stations are affected by the presence of Cenozoic formation, the material of which is lighter than normal. This will be referred to later. We may conclude, I think, that there is practically no relation between the sign and the size of the Hayford anomalies and the character of the topography on which the stations are located.

We find entirely different conditions in regard to the Bouguer anomalies. The size of the anomaly without regard to sign at coast stations is 0.021, practically the same as for the Hayford method of reduction. This is, of course, due to the fact that there is very little relief in the topography at the coast. The size of the Bouguer anomaly for stations in the mountainous regions above the general level is 0.111 dyne. The range is therefore 0.090 dyne.

When we consider the mean anomaly with regard to sign for the Bouguer method of reduction, we find a range for the groups from +0.017 to −0.110 dyne. This is a total range for the groups of 0.127 dyne. If we should consider the individual stations, we should find much wider ranges for the Bouguer values than for the Hayford values. The total range for the Hayford values is from +0.059 to −0.093. The total range for the individual stations for the Bouguer reduction is from +0.057 to −0.229.

The values given above are conclusive proof that the condition of isostasy exists to a rather remarkable degree, and that the theory that the topography of the earth is not compensated for by a lack of density under the continents and by an excess of density under the oceans is far from the truth.

The fact that the country as a whole is in a high state of isostatic adjustment is evident from the values given above, but there are local deviations from normal which may be due to a number of causes. They may be due to departures from the state of perfect isostasy, to an erroneous method of distributing the compensation horizontally from the station, to an erroneous method of distributing the compensation vertically with respect to depth, to erroneous values employed for the density of the topography, or to an erroneous depth of compensation; or they may be due to the presence of material heavier or lighter than normal close to the station but below sea-level. This extra or deficient density may or may not be compensated for in lower portions of the lithosphere.

There were made, during the investigation, certain tests which throw some light upon the causes of the gravity anomalies.

It has been held by some that the compensation of topography is not distributed locally under the topographic feature, but is extended horizontally to some unknown distance. It does seem improbable that the compensation should be directly under the topographic feature and not extended horizontally to a certain extent. At the same time, it is equally improbable that the compensation should be extended horizontally and uniformly out to any definite distance from a station. It would seem to be more probable that the compensation is distributed regionally, with the greater amount of the compensation directly under the topographic feature, and that it diminishes in amount with the distance from the feature.

A test was made to show whether local distribution or regional distribution was the more probable. The distribution in each case in the regional method was uniform. The method employed was to take the average elevation of the topography within a certain distance of the station. In one case the distance was 18.8 km., in another 58.8, in a third case 166.7 km. from the station. With the average elevation within these areas, a computation was made of the effect of the compensation, which was supposed to be uniformly distributed out to the limit of the area and also uniformly distributed from the surface to the depth of compensation.

The method of distributing the compensation horizontally necessarily leads to some error, for, as a matter of fact, the compensation of each topographic feature should be distributed regionally with respect to that particular feature. But such computations would be extremely laborious and it is believed that the results would not be materially different from those which were obtained. That erroneous results might be obtained for a single station is readily perceived when we consider that the station may be on a plain or plateau, say 167 km. in radius, and that just outside of this area there are massive mountain masses. According to the theory of regional distribution of the compensation, the compensation of the mountain masses should be extended under the plains; it should therefore have an effect on the computed gravity at the station. It would tend to make the computed value of gravity at the station smaller than it would otherwise be. On the other hand, we might have a station in a mountain mass of, say, 167 km. in radius, with plains surrounding the mass. In this case all the compensation of the mountain mass would be used in the computation of the corrections to gravity. Some of the compensation should be distributed for a distance of 167 km. out into the plains.

There were 124 stations in the United States which were used in the investigation of the regional distribution of compensation. We shall speak of the three regional distributions as Zones K, M, and O,[1] since the distances given above are the outer limits of those zones. The anomalies for the local and for the three regional distributions of compensation are shown in Table II for the 124 stations.

The values in this table give no evidence whatever in favor of any one method of distribution over the others. This is probably as it should be, for most of the stations considered were in topography of low relief. When a station is on a plateau or a plain, it is evident that the method of distribution of the compensation has very little effect on the anomaly. If the topography were of exactly the same elevation throughout the zone, the local and regional distribution of compensation would give absolutely the same value. The difference in the effect would increase with the increase in the difference in elevation of the topography in different parts of the zone. While some of the stations might have larger anomalies by some one of the methods than by the others, there would be other stations for which the reverse would be true, and the mean anomaly for all the stations by each method would necessarily tend to be the same.

TABLE II

| | Anomalies | | | |
|---|---|---|---|---|
| | Local | Regional | | |
| | | Zone K | Zone M | Zone O |
| Mean with regard to sign.......... | −0.002 | −0.001 | −0.001 | −0.002 |
| Mean without regard to sign....... | 0.020 | 0.019 | 0.020 | 0.020 |

We may assume, as was done when considering the relation of the anomaly to the topography, that that method of distribution is most nearly the truth which has the smallest variation in anomaly for different classes of topography.

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[1] This refers to the zones used in computing the effect of topography and compensation. See Special Publication No. 10.

The 124 stations under consideration were arranged in five groups, depending upon the topography. The anomalies with and without regard to sign for the local and the three regional distributions of the compensation are shown in Table III.

The mean anomaly with and without regard to sign for the several groups and for the various methods of distributing the compensation does not throw very much light upon the question of which method is nearer the truth, although a careful analysis of the table will, it is believed, indicate that the distribution regionally to the outer limits of Zone O, 166.7 km., is not as probable as the local distribution of compensation or the regional distribution out to the limits of Zone K, 18.8 km., or Zone M,

TABLE III

LOCAL AND REGIONAL ANOMALIES

| | LOCAL COMPENSATION ANOMALIES | REGIONAL COMPENSATION ANOMALIES | | |
|---|---|---|---|---|
| | | Zone K | Zone M | Zone O |
| FOR 18 COAST STATIONS | | | | |
| Mean with regard to sign.......... | −0.004 | −0.004 | −0.004 | −0.006 |
| Mean without regard to sign....... | 0.018 | 0.018 | 0.018 | 0.020 |
| FOR 25 STATIONS NEAR THE COAST | | | | |
| Mean with regard to sign.......... | −0.002 | −0.001 | −0.001 | −0.001 |
| Mean without regard to sign....... | 0.022 | 0.021 | 0.021 | 0.022 |
| FOR 39 STATIONS IN THE INTERIOR, NOT IN MOUNTAINOUS REGIONS | | | | |
| Mean with regard to sign.......... | +0.001 | +0.002 | +0.002 | +0.003 |
| Mean without regard to sign....... | 0.017 | 0.018 | 0.018 | 0.017 |
| FOR 22 STATIONS, IN MOUNTAINOUS REGIONS, BELOW THE GENERAL LEVEL | | | | |
| Mean with regard to sign.......... | 0.000 | +0.001 | +0.003 | +0.006 |
| Mean without regard to sign....... | 0.017 | 0.017 | 0.018 | 0.019 |
| FOR 18 STATIONS, IN MOUNTAINOUS REGIONS, ABOVE THE GENERAL LEVEL | | | | |
| Mean with regard to sign.......... | +0.003 | +0.003 | 0.000 | −0.010 |
| Mean without regard to sign....... | 0.018 | 0.018 | 0.017 | 0.020 |

58.8 km. The greatest range for the mean anomalies with regard to sign is for Zone O and for mountainous regions where the stations are below and above the general level. The range here is from +0.006 to −0.010, which is 0.016 in all. This range is almost as large as the average anomaly for the United States without regard to sign. The largest range for the other methods of distribution is 0.007.

We should expect the regional and local anomalies to be approximately the same for all of the stations not in mountainous regions, but we should also expect that the local and regional anomalies would differ for the stations where the relief is great. Where the station is below the general level, the computed value of gravity is less because some of the compensation of the mountains is distributed closer to the station than it would be by the local distribution. Where the station is above the general level, the computed value of gravity is greater because some of the compensation of the local topography is distributed under the contiguous valleys.

We may conclude, I think, that the solution of the problem of local distribution of compensation of the topography is indeterminate to a certain degree; that is, that any one distribution is as probable as any other one, out to a distance of 59 km. from the station. It is possible and, in fact, probable that this uncertainty may extend to a distance somewhat greater than 59 km., but it is very probable that it does not extend to a distance of 167 km. from the station. This conclusion is based upon the geodetic evidence, as furnished by the gravity anomalies, and has no connection with geological evidence. Any decision as to whether one method or another is the more probable within the distance of about 60 km. should be left to the judgment of geologists. It is of course possible that, with more geodetic data available, geodesists may be able to throw additional light on this subject.

It should be remembered that when making the test for the most probable method of distributing the compensation horizontally the anomalies are treated as if they were due only to the method of distribution. As a matter of fact, they are probably due to a number of causes, and this fact has some effect on the results of the computation, but it is believed that its effect is small.

When the researches in isostasy and in the deflection of the vertical were started, it was assumed that the compensation of topography was complete, that it was distributed directly under the topographic feature, and that it was uniform with respect to depth. This method of distribution vertically and horizontally was continued in the computations connected with the researches in gravity and isostasy. The depth of compensation derived from investigations of the deflection of the vertical, which was considered to be of the greatest probability, was 122.2 km.[1]

As it is probably true that the gravity anomalies may be due to an erroneous depth of compensation, it was decided to compute a new value for the depth, based upon gravity observations alone. The results of these computations, with numerous tables, are given in Special Publication No. 40, and only the results need be given in this paper. In the investigations from which were determined the most probable depths from gravity determinations, there were used only the 219 stations in the United States. It was impossible to use the gravity stations outside of the United States because of lack of detailed data.

TABLE IV

| | DEPTH OF COMPENSATION IN KILOMETERS | | | | | | |
|---|---|---|---|---|---|---|---|
| | 42.6 | 56.9 | 85.3 | 113.7 | 127.9 | 156.25 | 184.6 |
| Mean anomaly with regard to sign, for all stations............. | +0.004 | +0.003 | 0.000 | −0.003 | −0.004 | −0.007 | −0.010 |

The depth 113.7 km., the one derived in the first investigation of *The Figure of the Earth and Isostasy from Measurements in the United States*, was used in making the reductions for compensation in the investigations of gravity. With the detailed information obtained from the computations it was possible to obtain the effect of the compensation for other depths. This was done by means of certain factors.

The mean anomaly with regard to sign for all the stations is shown in Table IV. The means without regard to sign for all of the stations used as a single group for the various depths of compensation had a range of only 0.002 dyne from 0.020 to 0.022. Owing to the small range, it is not necessary to show the means without regard to sign in the table. The anomalies in this table have not a very wide range, and therefore there is no very strong evidence to show that any one depth among the intermediate depths is much better than the others. The evidence, such as it is, favors the depth of about 85 km.

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[1] See *Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy*, p. 54.

TABLE V

ANOMALIES AT DIFFERENT DEPTHS OF COMPENSATION

| Character of Topography | Number of Stations | Mean Anomalies with Regard to Sign for Depth in Kilometers | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 42.6 | 56.9 | 85.3 | 113.7 | 127.9 | 156.2 | 184.6 |
| Coast. . . . . . . . . . . | 27 | −0.002 | −0.003 | −0.006 | −0.007 | −0.008 | −0.009 | −0.009 |
| Near coast. . . . . . | 46 | + .002 | + .002 | + .001 | + .001 | + .001 | + .001 | + .001 |
| Interior, not in mountainous regions. . . . . . . . . | 87 | − .003 | − .002 | − .001 | + .001 | + .001 | + .003 | + .005 |
| Mountainous regions, below general level. . . | 36 | .000 | .000 | .000 | − .001 | − .001 | − .002 | − .003 |
| Mountainous regions, above general level. . . | 20 | +0.021 | +0.016 | +0.009 | +0.003 | +0.001 | −0.003 | −0.006 |

In order to get stronger evidence as to the most probable depth of compensation, the stations were divided into groups according to the topography, as was done in several other tests. The mean anomalies without regard to sign for the seven depths considered had a total range of 0.009 from 0.017 to 0.026. Each of these mean anomalies came in the group of stations in mountainous regions, above the general level. The maximum range for any other group of stations was 0.004 and that occurred in the mountainous regions where the stations are below the general level.

The means with regard to sign varied for the different depths and the different classes of topography. These means are shown in Table V.

It will be noticed that there is only one group for which there are very decided changes in the mean anomaly with regard to sign—

stations in mountainous regions, above the general level. The anomaly is +0.021 for a depth of 42.6 km. and it is −0.006 for a depth of 184.6 km.

Computations were made to obtain the most probable depth from all the gravity data for the 219 stations in the United States. Where all stations were used, the depth was found to be 67.1 km. It was realized that the stations on topography which was not in mountainous regions were not well adapted for the determination of a depth of compensation. Owing to the low character of the topography, the effect of the compensation was nearly the same regardless of the distance from the station to which it was extended. This is due to the fact that the attraction of an indefinitely extended disk containing a certain mass but of indefinite thickness will exert the same attractive force on a given mass regardless of how far from the disk the mass is placed. It is assumed, of course, that the attracted mass is over the center of the disk. We can see, therefore, that where the compensation is nearly the same in amount under a unit area for an indefinite distance around the station it would, although a number of kilometers in thickness, attract the pendulums at a station by the same amount regardless of the thickness of the disk or column of compensation.

The condition is different in the mountain regions for those stations which are above the general level, for there the topography near the station is comparatively limited in horizontal extent and the attraction of the compensation will depend upon the depth to which the compensation is extended. The closer to the station the greater of course will be the effect of the compensation and the larger will be the plus value of the anomaly observed, minus computed gravity. Where the compensation is extended to a great depth, the effect of the compensation is decreased, the computed value of gravity is necessarily larger, and the anomaly tends to be negative.

After consideration of all the facts, it was decided to determine the most probable value of the depth of compensation from gravity data by using only the stations in the mountainous regions below and above the general level. This was done and the depth resulting was 95 km.

It is interesting to note that, in the deflection of the vertical investigations, depths of compensation were determined for a number of groups, in addition to a depth for the whole country using all the stations as one group.[1] When we use the groups which are in mountainous regions and give the value of the depth of compensation derived from each group the same weight, it is found that the depth of compensation, as derived from deflections of the vertical data, for stations in mountainous regions only, is 97 km. It is rather remarkable that practically the same depth should be obtained from such widely different geodetic data. It is believed that the mean of these two values, or 96 km., is about the best value that is available at present from all geodetic data. As in other tests made during the investigation of gravity and isostasy, it was necessary to assume that all of the anomalies were due to the erroneous depth of compensation when the derivation of the most probable depth was made. This necessarily places some uncertainty in the depth of compensation, although it is believed that the uncertainty due to that cause is moderate in amount. It is probable that the best depth of compensation which will be derived from more geodetic data will be somewhere between 80 and 130 km. This, of course, is on the theory that the compensation is distributed uniformly from the surface or from sea-level to the depth of compensation.

The writer does not believe, as was stated earlier in this paper, that the compensation is distributed locally and uniformly to the depth of compensation. It is possible that the compensation may be distributed by some other method. It is probable that there is no method of distribution that is general, that is, applicable to each local area in the country. It seems to be most probable that the compensation varies from place to place and that the greater portion of the compensation may be near the surface in one place and lower down in another, or that it may be distributed throughout a considerable depth with varying amounts at different depths.

A computation was made, but the results of this do not appear in Special Publication No. 40, which showed the depth of the disk within which all of the compensation should be concentrated in order to have its attractive effect equal to the effect of the compensation uniformly distributed from the surface of the earth to a depth of 113.7 km. In other words, if all of the compensation were contracted to the disk at the particular depth, it would have the same effect as the uniform distribution.

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[1] See *Supplementary Investigations in 1909 of the Figure of the Earth and Isostasy*, p. 58.

If the compensation is distributed regionally to a distance of 10 km. from a station the disk within which all of the compensation is supposed to be concentrated must be placed 21.3 km. below the station. With regional compensation distributed to a distance of 20 km., 60 km., or 100 km. from the station, the depth of the disk becomes respectively 28.6 km., 41.2 km., or 45.5 km. If the compensation is started at sea-level instead of at the surface of the ground, each of the depths given above should be increased by about 1 km.

These depths are of particular significance, for they represent what may be called the effective center of the compensation on the basis of uniform distribution with respect to depth and with a depth of 113.7 km. This depth, as shown by certain tests, gives practically as good results as what may be called the most probable depth of 96 km. It is significant that there can be a variation in the depth of as much as 18 km. without materially affecting the anomalies.

It is reasonably certain that the effective depth as given above would be practically the same for all of the intermediate depths used in the computations to show which was the most probable depth. We may conclude, therefore, that the figures given above actually represent the effective center of the compensation, regardless of the method of distribution of the compensation. If, for instance, the compensation were considered to be confined to a zone about 20 km. in thickness, the center of that zone would have to be between 30 and 50 km. below sea-level. If the compensation is distributed according to the Chamberlin method,[1] the greater portion of the compensation would necessarily have to come within 100 km. of the surface, but there would be part of it at some distance below that depth.

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[1] See *The Figure of the Earth and Isostasy from Measurements in the United States*, p. 160.

It would not be a very difficult matter to draw curves representing different methods of distribution of compensation which would have effective depths of the compensation equivalent to those shown above for uniform distribution. If we have the effective center of compensation about what it is for the uniform distribution, then, under any method of distribution of compensation, the greater portion of the compensation would be between the sea-level surface and about 100 km.

It may be concluded from a study of the gravity data and also of the deflection of the vertical data that there is no geodetic evidence which favors any particular method of vertical distribution of compensation. Anyone is therefore free to use a method of distribution which best serves his purpose or which may fit the particular theory he may hold in regard to the constitution of the earth's lithosphere. But, in order to secure results which are as accordant as those given in the latest report of the Survey, the effective depth of compensation must be between 30 and 50 km.

It was noticed early in the investigations of gravity and isostasy that there were apparently some relations between the gravity anomalies and the densities of the materials at the surface of the earth close to the station. This subject was treated briefly in Special Publications Nos. 10 and 12, which gave the results of the earlier investigations of gravity and isostasy. With the additional material available from other countries as well as from the United States for the most recent investigations of gravity and isostasy, these relations between the gravity anomaly and the surface density are shown to be stronger.

In the United States the stations on the dense rock which belongs to the pre-Cambrian formation have anomalies which tend strongly to be positive. This is an indication that under the station the material of this formation extends to a considerable depth where the gravity anomaly is large.

It was found that the stations on the pre-Cambrian formation in Canada did not have the tendency to be positive that was shown in the United States. This may be due to the extensive areas covered by this formation in Canada. As was stated above, the attraction of a disk of material of indefinite extent is independent of the distance of the attractive mass from the disk; therefore, if we should have in Canada a station on an extensive area of pre-Cambrian formation where the material is of uniform thickness, and if this material were compensated for by a deficiency of material below it, then the compensation would have an effect which would practically counterbalance the effect of this denser material which is near the surface.

In India there are only eight stations on the pre-Cambrian formation, six of them having positive anomalies and two negative. But the mean with regard to sign of the anomalies is nearly zero. It may be possible that the small number of stations on this formation in India prevents the stations there from showing the same relation to the formation that we have in the United States. It is worthy of note that each of the areas of the pre-Cambrian formation in the United States on which stations are located is rather small in horizontal extent. If we should have a pre-Cambrian formation 10,000 feet thick under a station with a density of the rock 10 per cent above normal, and if the formation extended 10 km. in all directions from the station, the effect of the increased density would be to increase gravity by +0.029 dyne. If this extra material were completely compensated for and the compensation were distributed uniformly to a depth of about 114 km., the negative effect of the compensation would be −0.003 dyne. The resultant would be +0.026 dyne, which is about the size of the average pre-Cambrian anomaly in the United States.

It was found that the anomalies at stations on the Cenozoic formation had a tendency to be negative both in the United States and in India. There were only two stations in Canada on this formation and they were both negative. It is probable that the reasoning employed above in regard to the pre-Cambrian anomalies will apply to the Cenozoic anomalies. The density of the material of this formation is in general about 5–10 per cent less than normal, and the presence of this light material near the station should have a greater effect on the value of gravity than the compensation of this material, if any, which would be lower down in the lithosphere.

If the Cenozoic formation should be of great horizontal extent and of uniform thickness, the effect of material of this formation would be offset almost entirely by the effect of the compensation if this lighter material were compensated for by an excess of material lower down in the lithosphere.

The mean anomaly with regard to sign for the Cenozoic stations in the United States was −0.007 dyne. In India it was −0.017 dyne. There were 31 stations in India on this formation and 20 had negative anomalies and 11 had positive ones. The positive anomaly in every case was comparatively small, the largest being 0.033 dyne. There were 10 of the negative anomalies larger than 0.032 dyne.

Since the publication of the results of the recent investigation of gravity and isostasy, data have become available in regard to a number of gravity stations established in the Pacific Coast states, during the summer of 1916. Of 13 stations established in southern California, each one has a negative anomaly, and the mean with regard to sign is −0.037. The largest one is −0.081. This is only slightly smaller than the anomaly of −0.093 at the Seattle station. Each of these stations in southern California is located on Cenozoic material.

There were 9 stations established during 1916 close to Seattle with 8 of them on the shores of Puget Sound. Eight of these stations were on Cenozoic formation, and 7 of these had negative anomalies. The mean anomaly with regard to sign for the stations in this vicinity which were established in 1916 is −0.033 dyne.

The writer does not wish to be understood as asserting that the Cenozoic or the pre-Cambrian material is the cause of the anomaly at the stations located on those formations. He does believe, however, that the abnormal density of the material of those two formations is the cause, or rather the principal cause, of the tendency of the gravity stations located on them to have anomalies of one sign. As was stated earlier in this paper, it is not possible from the data now at hand to tell whether or not the area covered by a Cenozoic or pre-Cambrian formation, where the sign of the anomaly agrees with the density of the surface material, is in isostatic adjustment. This is due to the fact that the compensation, if present, is so far from the station that its attractive effect is very small in comparison with the effect of the deficiency in density in the materials close to the surface and under the station.

It seems probable that we may be able to predict with some accuracy a gravity anomaly on a Cenozoic or pre-Cambrian formation when we know the latitude and elevation of the point of observation and make a correction for the topography of the world and its compensation and apply a correction for the negative or positive attraction of the deficiency or excess of matter in the Cenozoic or pre-Cambrian formation. This, of course, is with the provision that the approximate depth and the horizontal extent of the material of these formations in the immediate vicinity of the station are known. It is also possible that where a station is located on a Cenozoic formation and has a positive anomaly the Cenozoic material is of slight thickness and is underlaid by pre-Cambrian or other extra dense material.

The stations in the United States on Paleozoic formations show a tendency to have negative anomalies. The mean anomaly with regard to sign is −0.009 dyne. The Mesozoic stations have a tendency to be positive with a mean anomaly with regard to sign of +0.011 dyne. There were so few stations on intrusive and effusive formations that it is believed that no definite results were obtained from a study of them. There were enough stations in the pre-Cambrian, Cenozoic, Mesozoic, and Paleozoic formations to enable one to state rather definitely that stations on any one of them have a decided tendency to have anomalies of a certain sign. There cannot, however, be any relation between the sign of the gravity anomaly and the density of the Paleozoic or the Mesozoic material, for, in general, the density of the material of those two formations is about normal.

Where the surface density is subnormal and the gravity anomaly is positive, it may be possible that there is denser material somewhat lower down in the lithosphere if the size of the anomaly is large. By large is meant somewhat above the average size of the anomaly without regard to sign. There are a number of places in the United States in which borings have disclosed the presence of crystalline rocks at varying depths below the surface where the surface material was light in density. Dr. David White, chief geologist of the United States Geological Survey, suggested to the writer that it may be possible to predict with considerable accuracy whether or not crystalline rocks are close to the surface under a station located on surface material of light density by considering the size and sign of the anomaly.

There has been considerable confusion in regard to the opinion of Professor Hayford and the writer as to the density of material between sea-level and the depth of compensation. Some assert that we hold that the density is 2.67 for all of this material except in so far as it is modified by the compensation. As a matter of fact, neither of us has made any assumption as to the absolute density of the material between sea-level and the depth of compensation. In the investigations of isostasy it is not necessary to know the absolute density in making computations of the effect of the compensation of the topography. It is the deviations from normal densities that are given sole consideration.

A great deal of the gravity anomaly is eliminated by the application of the effect of topography and compensation, but it is certain that the remainder of the anomaly cannot be eliminated by applying the actual density of the topography in the computations. The density of 2.67 was used for all the land topography, while there are local variations in the density of material amounting to 10 per cent or more. It is, however, impossible that the true densities, if applied, could have reduced materially the average gravity anomaly. There is not enough topography to account for the gravity anomaly. It is of course probable that in many cases the anomaly would be slightly changed if a true density were used. What applies to the density of the topography will of course apply also to the density of the compensation. There is not enough compensation, however distributed, to account for most of the anomalies. As the effect of the compensation is the opposite of that of the topography, the resultant effect is smaller than the effect of the topography alone. We must conclude that no method of distributing compensation applied generally to the country or to the world will eliminate the gravity anomalies which we now have.

We must go below sea-level and below the beds of the oceans to find the cause of the anomalies. This necessarily takes the geodesist into the realm of geology, and it is there that he needs the assistance of geologists who are familiar with the geological history of the outer portions of the earth's lithosphere and of the existence of materials that deviate from normal density.

As to the process by which isostatic adjustment occurs, we must consider this largely a matter of speculation. There is no geodetic evidence on the subject. No one can say that he knows. Of many theories or opinions one is inclined to accept that which appears to be most reasonable to him.

We may summarize the contents of this paper as follows: We have sufficient geodetic data to prove that, for large areas, such as that of the United States, considered as a whole, the condition of isostasy is nearly perfect. The data also prove that the local deviations from perfect isostasy are not more than about 25 per cent on an average. If, however, we consider that the abnormally heavy or light material which is found under a number of gravity stations is compensated for by deficiencies or excesses of density lower down in the lithosphere, we may assume that the deviation locally from perfect isostasy is of the order of 10 or 15 per cent rather than of 25 per cent. The writer believes that this assumption is justified.

There is no geodetic evidence to show whether or not regional distribution out to a distance of 58.8 km. from a station is more probable than the local distribution immediately under each topographic feature. There is geodetic evidence which makes the local distribution of compensation or the distribution regionally within 58.8 km. more probable than the regional distribution out to a distance of 166.7 km. from the station. It may be possible, though the writer believes it improbable, that there is a distance between 58.8 km. and 166 km., which would give a more probable regional distribution than the distances tested.

The geodetic evidence favors about 96 km. as the depth of compensation if the compensation is assumed to be distributed uniformly between the earth's surface or sea-level and the depth of compensation. There is no geodetic evidence to show that any one method of distribution of the compensation is more probable than other methods. It is reasonably certain that any method of distribution of compensation must have the effective depth of the compensation at a distance of from 30 to 50 km. below sea-level. By effective depth is meant such a distance below sea-level that the effect of all the compensation condensed into a thin layer at that depth would be the same as the attraction of the compensation distributed from the surface to the depth of compensation.

The absolute density of the material between the depth of compensation and the surface of the earth is not considered by the geodesist in making the corrections for the effect of compensation. It is only deviations from normal density that he considers, and it is not necessary even to know what the normal density is.

It must be concluded that the cause of the gravity anomalies is located below sea-level, and the evidence points to the probability that at least a large part of the anomaly is due to extra heavy and extra light material in the outer portions of the lithosphere which is below sea-level.

There have been found decided relations between the sign of the gravity anomalies and the geological formation. This is evidently due to the abnormally heavy and abnormally light materials in the pre-Cambrian and Cenozoic formations, respectively. There were found relations between the Paleozoic and Mesozoic formations and the sign of the gravity anomalies, but it is not evident what has caused this relationship.

There is practically no relation between the character of the topography and the sign and size of the gravity anomaly by the isostatic method of reduction. This is a very strong argument in favor of isostasy because all other methods of making gravity reductions which do not consider isostatic compensation show most decided relations between the size and sign of the anomaly and the character of the topography.

The use of gravity stations in other countries with those in the United States gave a gravity formula whose constants were practically the same as the constants of the gravity formula derived in 1912 from data at 124 stations in the United States alone. In the

1917 formula there were 358 stations used, 216 of which were in the United States.

There was not available for the foreign stations such detailed information as was available for the stations in the United States, and it was therefore not possible to utilize the foreign stations in making certain tests, but the geodetic evidence available for the foreign stations makes it practically certain that isostasy is in as nearly a perfect state in those countries as it is in the United States.

There is no geodetic evidence disclosing the process by which the isostatic adjustment takes place. This is a matter for speculation rather than proof.

The subject of isostasy is a very important one and a very broad one, and the work that has already been done is very small in comparison with what must be done in order to discover the laws of the distribution of compensation, the extent to which it is perfect, and the cause of the unexplained deflections of the vertical and the anomalies of gravity. The field is broad, and it is necessary that other scientists than geodesists should enter it. It is especially desirable that geologists and geophysicists assist in the investigation.